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SHIPYARD PLANNING MODEL FEASIBILITY STUDY.(U)

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FINAL REPORT.

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PREFACE

Improved shipyard planning is a requisite to a continually viable U.S. shipbuilding industry. As ships become more complex and more varied, and the number of ships under construction varies widely, it is necessary that the planning by shipyards be sensitive and responsive to this complex, dynamic economic environment to ensure construction costs are minimized and profitability is maintained. Unfortunately, planning guides currently employed have apparently not been effective in attaining what might be considered optimal construction scheduling. Sophisticated planning models and techniques have been developed; however, they generally have been too complex to be useful to the industry, and have often not been validated empirically.

The research described in this report evaluated the feasibility of deriving empirical models to guide ship construction planning by performing a macro-analysis of available ship construction data. The underlying hypothesis tested in the model development was that there is an optimal construction period for ships resulting from a decrease in productivity as manloading increases because of unproductive effort associated with management, intercommunication, scheduling, etc., and an increase in productivity as manloading increases because of efficiencies arising from division of labor, rate of labor application, etc.

A relatively short term, low resource effort constrained by data availability, the investigation established that planning models can be developed empirically. The models evolving from this preliminary research can be used to estimate the optimal construction time for ships (by type), and the anticipated manhour expenditures for that construction period. They also permit an assessment of the impact on construction manhours of deviating from the optimal construction period. Although not addressing all classes and types of ships, nor all dimensions of shipyard planning, models of the type presented should result in lower manhour expenditures in ship construction.

Valuable assistance has been provided to the study by several individuals, including Dr. Thomas C. Varley, Office of Naval Research, sponsor of the research, Captain E. Robert Burdon, NAVSEA monitor for the project, and Dr. Franz A. P. Frisch, currently on the staff of the Defense Systems Management College. We are indebted to these people for their active participation in, guidance to, and review of the effort.

SUMMARY

In response to a need for improved guides to ship construction planning, a short-term research program was sponsored by the Office of Naval Research to determine if it is feasible to derive empirical models which reflect the impact of construction time and manloading on the resource requirements of ship construction. An hypothesis which defines the effects of the manloading and construction period on productivity was proposed and subsequently validated. Inherent in the hypothesis is the existence of optimal construction periods and construction manloadings for ships.

A macro-analysis of ship construction data, the study resulted in the development of analytical models for individual ship types which define construction manpower requirements in terms of the weight of the ship and the length of the construction period. In addition, it was determined that optimum construction periods and associated minimum manhour requirements do exist for ships, and that this optimum scheduling is attained by an appropriate rate of manpower allocation.

Limitations in the amount of readily accessible data precluded the development of specific models applicable to all ship types. Since the research was considered preliminary, emphasis was given to isolating effects reflected in the available data rather than expanding the scope to include as many types of ships as possible. However, the analysis of the small data sets of ships for which models could not be developed further supported the existence of the effects reflected by the analytical relationships (no data sets refuted the hypothesis). Consequently, it is likely that the effects are relevant to all ship types, and that with adequate data, similar planning models can be developed for all ships.

Additional data was received throughout the six-month period of this preliminary research; there was not time to incorporate data received in the later phases of the study in the model construction. It was analyzed briefly to determine if it refuted the hypothesis; none did.

"---Technical risk because of the complexity of ship design, schedule risk because of the four- to seven-year period needed to construct a ship, and cost risk because of the difficulties of predicting the costs of the multiple elements of the ship construction process."[1]

The present effort will help mitigate, or at least better understand, the schedule and cost risks attendant to ship procurement.

B. OUTLINE OF THE REPORT

The remainder of this report discusses progress made to date toward development of a resource planning model. Section II describes the basic hypothesis proposed and investigated, and presents some of the theoretical bases of the approach. Section III discusses the analytical methodology used in empirically testing the hypothesis, describes the data used, and outlines results of the study. Because of the proprietary nature of some of the information, selected data used in the analysis have been deleted from this report. To prevent proprietary data from being extrapolated from the findings, the results are presented, as necessary, in a normalized form. Section IV presents conclusions based on work accomplished to date and discusses recommendations for further development and refinement of the approach. A bibliography of previously performed relevant work is also presented.

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1. "Naval Ship Procurement Process Study," Assistant Secretary of the Navy, Manpower Reserve Affairs and Logistics, Final Report, July 1978.

I. INTRODUCTION

Under Contract No. N00014-78-C-0866 with the Office of Naval Research, Doty Associates, Inc. (DAI) performed a preliminary investigation of the feasibility of developing models for improved shipyard planning. The study, which involved a macro-analysis of relevant ship construction data, essentially corroborated a proposed hypothesis describing an interaction between resource allocation and resource requirements. Algorithms defining the relationship between construction time and labor requirements evolved which can be used to estimate optimal ship construction periods and associated manhour expenditures and to evaluate the impact of schedule changes on these expenditures. These represent important guides to shipyard planning.

Initiated in September 1977, the research has concentrated on two objectives:

- establishing a theoretical foundation for proposed model(s); and
- determining the extent to which theory can be demonstrated empirically.

While neither objective has been fully achieved, it is believed that sufficient progress has been made within the limited resources of this study to show that the approach developed can become a practical planning tool. This report describes the work and findings to date.

A. BACKGROUND

The Office of Naval Research has identified and is pursuing several specific problems of interest in the general area of Systems Acquisition Research and Technology. Among the problem areas identified is a need for the Navy to better understand the scheduling and planning functions in private shipyards.[1]

1. Department of the Navy letter ONR:431:TJ:dmf, dated 29 June 1977.

In this regard, ONR has posed several key questions:

- How do shipyards schedule rates of application of resources in a constrained environment?
- Are there key determinants for a best or most economic building speed, and are the determinants ship or shipyard related?
- Are there procedures available that can be incorporated into the prime contract for assuring the success of the planning function, and if so, what is a reasonable cost for such a system?
- At what phase, if any, of the acquisition process should such a system be available to the Navy and/or the contractor?

In labor intensive industries such as shipbuilding, the total resources required to complete a task are affected by several factors; e.g., the time schedule imposed, the total manpower assigned to the task, the mix of skills in the work force, and the facilities available. The impact and interaction of these determinants of productivity, especially in the ship construction industry, are not well understood. Intuitively, it would appear that if the interactions could be defined, it would be possible to maximize productivity (minimize resources required) for a given task.

The purpose of this study has been to perform a preliminary assessment of the relationships between factors affecting productivity in shipyard construction and to structure the resultant analytical relationships into a model to effect optimal scheduling of ship construction within a shipyard.

Such a resource planning model would provide a mechanism to answer the questions posed by ONR. These questions relate, in turn, to the broader objectives as perceived by the Assistant Secretary of the Navy for Manpower, Reserve Affairs and Logistics. In his comprehensive study of Naval ship procurement, it is pointed out that there are three primary risk areas in this activity:

"---Technical risk because of the complexity of ship design, schedule risk because of the four- to seven-year period needed to construct a ship, and cost risk because of the difficulties of predicting the costs of the multiple elements of the ship construction process."[1]

The present effort will help mitigate, or at least better understand, the schedule and cost risks attendant to ship procurement.

B. OUTLINE OF THE REPORT

The remainder of this report discusses progress made to date toward development of a resource planning model. Section II describes the basic hypothesis proposed and investigated, and presents some of the theoretical bases of the approach. Section III discusses the analytical methodology used in empirically testing the hypothesis, describes the data used, and outlines results of the study. Because of the proprietary nature of some of the information, selected data used in the analysis have been deleted from this report. To prevent proprietary data from being extrapolated from the findings, the results are presented, as necessary, in a normalized form. Section IV presents conclusions based on work accomplished to date and discusses recommendations for further development and refinement of the approach. A bibliography of previously performed relevant work is also presented.

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1. "Naval Ship Procurement Process Study," Assistant Secretary of the Navy, Manpower Reserve Affairs and Logistics, Final Report, July 1978.

II. THE HYPOTHESIS

Quantitative procurement resource models are typically based on physical and/or performance characteristics of the commodity to be procured. Often, they rely on a projection from historical experience with identical or analogous goods or services purchased in the past. Rarely, however, do they explicitly reflect the effects of the efficiency of resource utilization. While this approach may suffice for relatively quickly-produced, assembly line items, it has been shown to be inadequate in estimating the resource requirements of more complex, long-term, and labor intensive projects. And, to the extent that prior studies have relied on historical data, the models and results obtained reflect actual performance achieved rather than the superior performance that might be achieved with a more judicious choice of program resource allocation.

This fault of traditional cost estimating techniques was noted earlier by Solomon.

> "It is convenient to partition approaches to cost estimation into two types: engineering and economic. By no means are these approaches mutually exclusive; however, they do differ in emphasis. The engineering approach refers to the estimate of costs of design entities which form a ship or some multiple of the same ship without specific reference to the overall shipbuilding program over time and/or the economic conditions of the industry for the relevant time period. The economic approach refers to studies which attempt to deal explicitly with industry and general economic factors without specific reference to individual ship design. Examples of these factors are relative utilization of factors of production, scale of output, market structure, etc. Again, while neither approach, in fact, absolutely ignores the other factors, the factors receive sufficiently different emphasis so as to consider the approaches to be dissimilar. It appears correct to state that the engineering approach has been dominant. The need to

> integrate both approaches is obvious, but this may not be accomplished by simply using both. Each approach must likely be modified in form and content to effect the desired integration leading to a total model."[1]

While the proposed approach to analyzing resource utilization in the shipbuilding process does not purport to be a total, integrated model, it does attempt to infuse a relatively typical engineering estimating technique with the economic concept of efficiency of resource utilization over time. Specifically, the hypothesis to be investigated is:

> It is believed that most ships are built to schedules that result in inefficient use of resources. However, it is proposed that an optimum manloading level does exist that results in most efficient utilization of the resources and that an optimum time duration exists for this utilization of resources.

Emphasis in this approach is placed on the labor required in shipbuilding for two principal reasons:

- labor accounts for half or more of the direct costs associated with traditional ship construction techniques; and
- while subject to variation due to such factors as availability and procurement quantity, shipbuilding material costs are, by comparison, generally independent of construction schedule.

The notion that the scheduling of manpower in labor intensive projects could be optimized to maximize productivity has been discussed extensively in the literature. According to Gertsbakh and Stern[2], no known exact solution exists for optimizing resource utilization in a system such as a shipyard in

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1. Solomon, H., "Methodological Problems in Estimating Costs of Shipbuilding Programs and Some Proposed Solutions," Technical Memorandum TM-80042, Institute for Management Science and Engineering, George Washington University, 1970.

2. Gertsbakh, I and Stern, H.I., "Minimal Resources for Fixed and Variable Job Schedules", OPERATIONS RESEARCH, Vol. 26, No. 1, January - February 1978.

which the schedule can vary. However, they have developed an algorithm which permits an approximate solution (the Entropy Informational Smoothing Algorithm for VSP--Variable Schedule Problems). It improves scheduling by smoothing total resources required, somewhat similar to graphical techniques currently used. But this algorithm, and others developed, do not consider the impact of allocation on efficiency or productivity.

A. THE INTIAL MODEL FORMULATION

It has been assumed that a curvilinear relationship similar to that in Figure II-1 exists between manhours required and construction time for different size ships. The curve is based upon an hypothesized model that assumes an explicit relationship between manpower, size of the ship (task), manloading, and productivity, namely:

$$M = aW \left(1 + bN + c \frac{W}{N}\right); \text{ where} \tag{1}$$

M = manpower (manhours) required for construction of the ship;
W = size (weight) of the ship;
N = the average construction workforce (manloading); and
a, b, and c are parameters of the equation.

The rationale for this equation is as follows. Let productivity (P) be defined as

$$P = \frac{W}{M}, \tag{2}$$

that is, productivity is viewed in terms of quantity of construction completed per unit of labor input (e.g., tons per manhour). Given this definition, Equation (1) implies that

$$P = \frac{1}{a\left(1 + bN + c \frac{W}{N}\right)}. \tag{3}$$

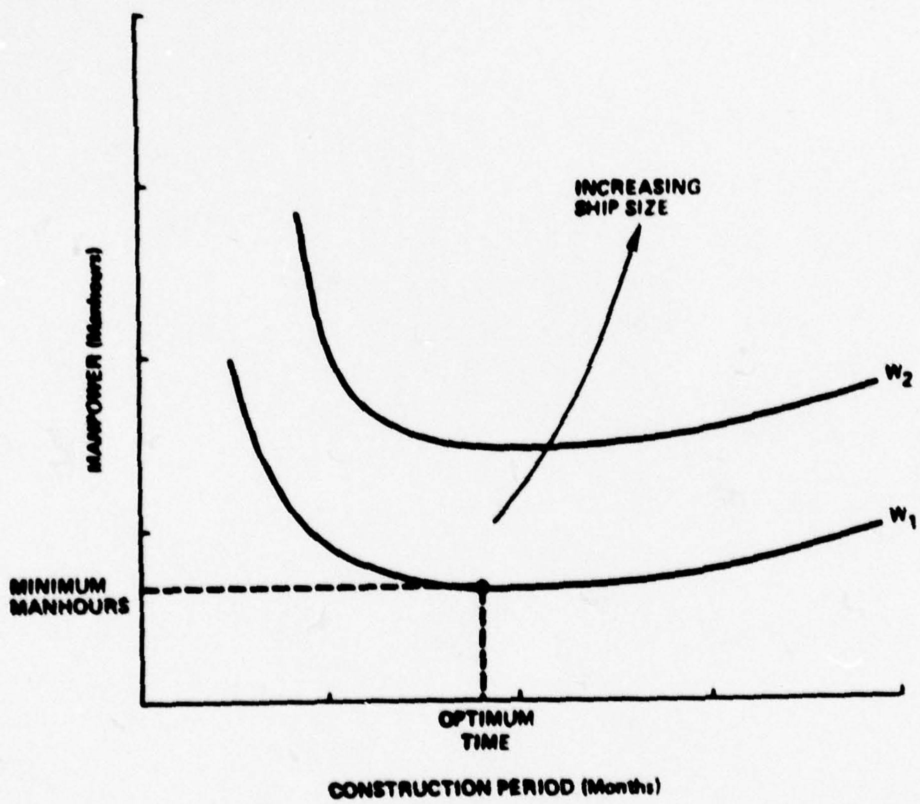

Figure II-1. Relationship Between Manpower and Ship Construction Schedule

The term bN reflects a decrease in productivity as manloading increases because of the unproductive effort associated with management and intercommunication. The term $c\,\frac{W}{N}$ reflects an increase in productivity as manloading increases because of the efficiencies arising from division of labor. (When each person is responsible for a smaller portion of the entire effort, measured by $\frac{W}{N}$, it is more likely that he can be assigned to a task best suited to his talents.) It is the interplay between these two terms that leads to an optimum value for N that minimizes M. The optimum results depend on W and the parameters a, b, and c. The latter will, of course, be functions of factors exogenous to the model such as shipyard characteristics and prevailing economic conditions.

Equation (1) can be viewed as applying to the entire ship construction project as implied above, in which case the variable W represents the total ship weight. Alternatively, and more generally, the model can be applied to portions of the total construction project, such as specific work breakdown structure (WBS) elements. In this case, W is a measure of work to be accomplished which is appropriate to the particular element (e.g., tons of steel for hull structure, feet of cable for electric plant).

B. MODIFICATIONS TO THE MODEL

To make the model more realistic and tractable to testing with actual shipbuilding experience data, several modifications were made.

- Substitution of Construction Period (T) for Manloading (N).

  This change was made because information on historical shipbuilding projects gives construction period directly while average manloading can only be inferred. The two variables are related through the identity $M=\lambda NT$, where λ represents the hours per unit of T worked by each man.

- **Free Exponents of the Variables.**

  Equation (1) sets the exponents of W and N (now T) in each term. There is no *a priori* basis on which to assume a value for these exponents. Therefore, the exponents were 'freed' to permit their statistical derivation and to provide the best model fit to actual data.

- **Reduce the Number of Parameters.**

  With the exponents of Equation (1) permitted to vary, the model requires that a large number of parameters (coefficients and exponents) be estimated. This, in turn, necessitates more data to establish greater confidence in the parameter estimates. Since available data sets are relatively small, the first term of the model was dropped. If sufficient data becomes available, the effect of this modification should be investigated further.

The form of the model resulting from these changes to Equation (1) is as follows:

$$M = aW^{b}T^{-c} + dW^{e}T^{f} \qquad c, f > o. \qquad (4)$$

The rationale for this model is essentially the same as that for Equation (1) and can be demonstrated as shown in Figure II-2.

- **Curve A.** As time available for ship construction increases, manpower required **decreases**. This indicates the increased productivity resulting from smaller manloading and the concomitant reduced requirements for management and intercommunications. This effect is reflected by the first term ($aW^{b}T^{-c}$) of Equation (4).

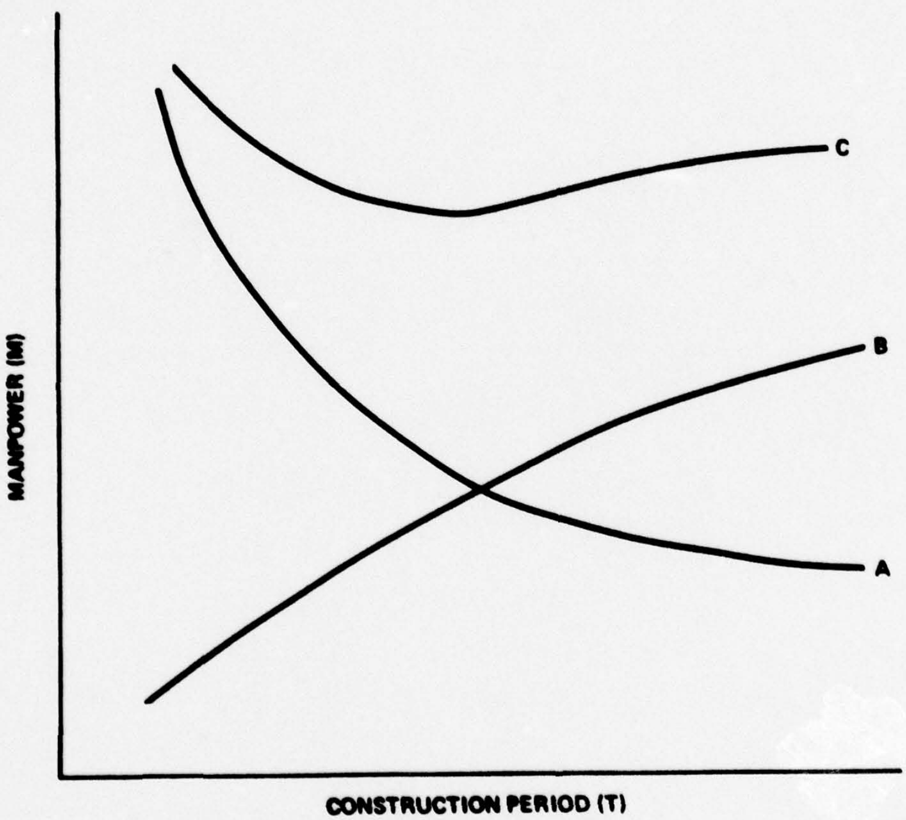

Figure II-2. Rationale for the Proposed Model

- Curve B. As the time available for ship construction increases, total manpower required increases. This indicates the decreased productivity resulting from smaller manloading and the associated imperfections in skills mix and division of labor. This effect is reflected in the second term (dW^eT^f) of Equation (4).

- Curve C. This relationship represents the cumulative impacts of Curves A and B and is, in fact, the model of Equation (4). It is convex with respect to the origin and possesses a single minimum point.

A similar model was proposed by Rhee.[1] The basis for his model was the assumption of a shipbuilding process production function which implies the existence of an optimum application of labor per unit time (e.g. manhours/day). This is analogous to the assertion of the proposed hypothesis that there is an optimum manloading level for a given shipbuilding project. A basic difference between the two approaches is that Rhee does not explicitly include any variable in his formulation which accounts for the size of the job to be accomplished as does the variable W in the present model.

C. OTHER CONSIDERATIONS FOR THE MODEL

Given the proposed model as represented by Equation (4), it only remains to estimate the parameters and exponents by statistically fitting the equation to appropriate historical data. However, there are other considerations which guide this process. Some of these are discussed here.

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1. Rhee, Tai Wook, "Modeling of Process Analysis and Its Application to the Shipbuilding Industry," George Washington University, School of Engineering and Applied Sciences, Serial T-289, 20 July 1973.

1. For a given type of ship (e.g., destroyer), it seemed reasonable to expect that, <u>ceteris paribus</u>, a larger (heavier) ship will require more time and labor to construct, with optimum planning, than a smaller ship. As shown in Figure II-3, this requires that the optimum construction period lengthen and associated manhours increase as ship size increases. In order for this to occur with the model as structured, the exponent b of the variable W in the first term of Equation (4) must be larger than the exponent e of variable W in the second term, with both exponents being positive. This causes Curve A of Figure II-2 to move upward faster than Curve B, as W increases, so that the minimum of Curve C moves up and away from the origin.

2. The behavior of the model at long construction periods is of interest. As seen in Figure II-4, a line is drawn from the origin so that it is tangent to the curve of the model at a point beyond the optimum schedule. If the model follows Curve A, then any straight line from the origin with a slope less than that of the tangent will never intersect the curve of the model. This implies that, below a certain size, a nominally constant work force cannot complete a particular ship no matter how long the construction period. If, however, there is an inflection point in the model curve beyond the optimum point so that it follows Curve B, it becomes theoretically possible for even a very small workforce to eventually complete the construction project, given all other necessary resources. Thus, Curve C, which represents the labor output over time of a specific constant-size workforce, will not intersect Curve A but does intersect Curve B. The latter outcome is intuitively preferred; for this to result, the value of exponent f of variable T in the second term of Equation (4) must lie between 0 and 1.

3. The proposed model relates required manpower to construction period for shipbuilding projects. Another important dimension in planning construction projects is the rate of application of manpower. Rarely is this rate constant throughout the construction period as reflected in Figure II-4. Normally, the number of personnel assigned to a given project varies over

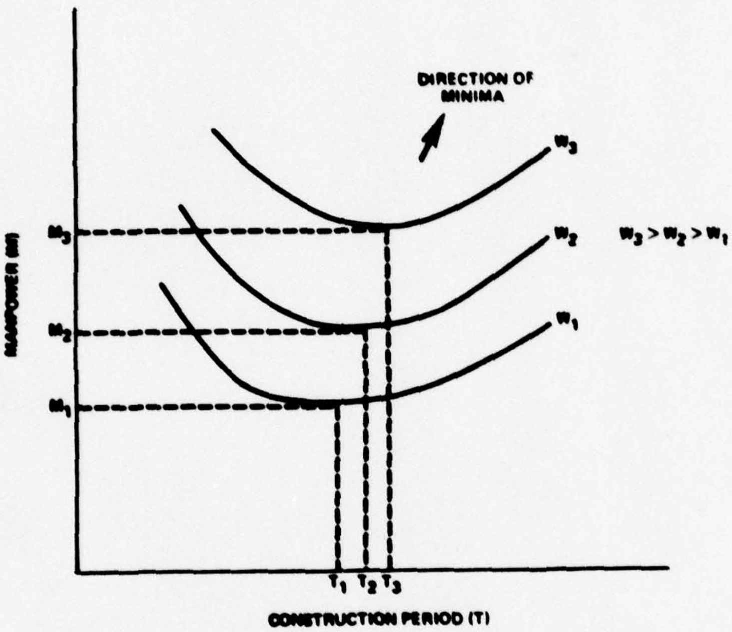

Figure II-3. Impact of Ship Size on Optimum Construction Schedule and Labor

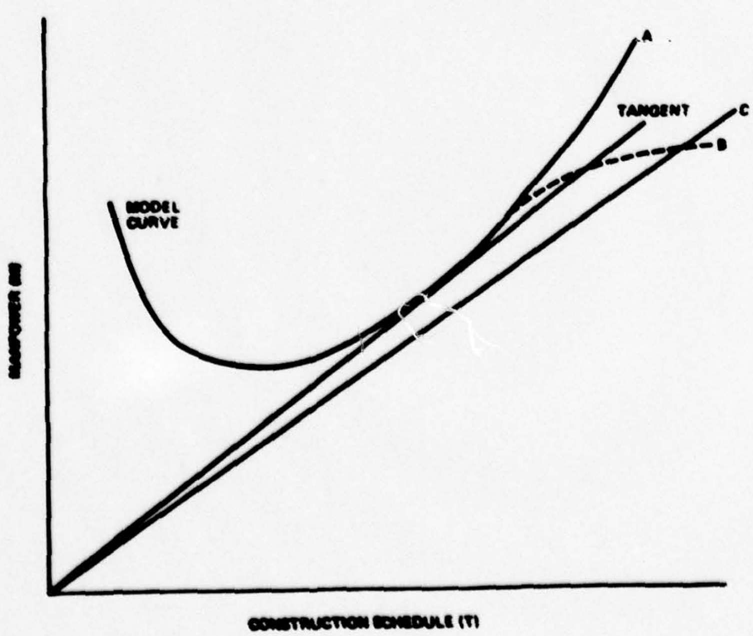

Figure II-4. Behavior of the Model at Schedules Longer than the Minimum

time. Figure II-5 shows two manpower distribution Curves, A and B, which are typical of shipbuilding practices. Also shown is the proposed model curve for a hypothetical ship. The project represented by Curve A builds up rather quickly to its peak manloading which is held constant until almost the end of the construction period. In this example, the ship is completed in the optimum construction period, T_A, which results in the minimum required manhours, M_A. The project represented by Curve B is identical in all aspects to Project A (e.g., same ship type, shipyard, skills, economic conditions) except for the scheduling of manpower. Getting off to a slow start, it attempts to catch up by assigning at time T_1 a higher peak manloading (reflected by slope of the curves) than Project A. Even though it may pass through the same completion point as Curve A (M_A manhours in time T_A), the construction is not finished in this case because of relatively inefficient manloading earlier in (and perhaps throughout) the construction period. The ship is not completed in Project B until time T_B at an expenditure of M_B manhours. Therefore, knowledge of the optimum construction time from the proposed model is not in itself sufficient to achieve minimum manhour expenditures; manloading must be applied at the proper rate throughout the construction period.

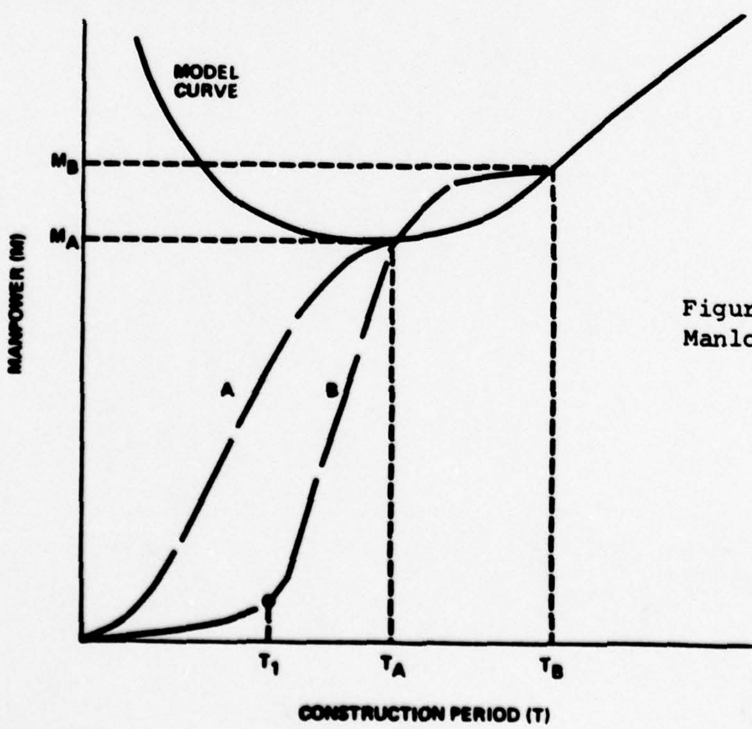

Figure II-5. Effect of Manloading Distribution

III. STUDY APPROACH

The research involved the following functional tasks: literature review, data collection, and model development and evaluation. The tasks, although intended to be performed sequentially, continued throughout the research period. Relevant reports of previous research and ship construction data continued to be collected beyond original efforts (and, in fact, continues still). The literature was reviewed to determine if the proposed hypothesis had been previously evaluated and to become familiar with prior research in ship construction planning. Additional data was integrated into the study as it was received. In later phases of the study, however, data received was only reviewed for compatibility with study results.

The analysis of the data included the review of scatter diagrams to identify trends and potential relationships among ship construction parameters, correlation analysis to evaluate the parameters as independent variables of planning models, and non-linear regression using Marquardt's method of gradient expansion for least squares fit to an arbitrary function[1/] to isolate the form and to develop the coefficients of the planning models. Models which reflect the relationship between manpower requirements of ship construction, the construction period, and the weight of the ship were developed for individual ship types.

A. DATA BASE

Historical data collected for the study encompassed the following:

- total manhours required to construct the ship,
- construction scheduling information (date of construction start, date of keel laying, date of launch, and date of delivery),

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1. Marquardt, Donald W., "An Algorithm for Least-Squares Estimation of Non-Linear Parameters," Journal of the Society of Industrial and Applied Mathematics, Vol. II, No. 2, Pg. 431-441, June 1967.

- light ship weights, and
- normalized rate of manpower allocation to ship construction (percent of total manpower over time).

A total of 43 complete data sets for ships constructed prior to 1970 were available for detailed study. The data base was structured into four major ship categories: (1) submarines (SSN and SSBN), (2) surface combatants (CG and FF, formerly DLG), (3) auxillaries (AD, AOE, and AS), and (4) amphibious ships (LPD, LST, and LPH). It was necessary to aggregate data by ship type due to the limited number of complete data sets available (the relative inaccessibility of construction manhour data limited the number of complete data sets).

B. ANALYTICAL PROCEDURES AND RESULTS

Preliminary analysis consisted of plotting scatter diagrams of construction manhours and shipyard schedule information for each ship category. The resulting plots indicated that: (1) stratification was necessary to account for differences in weight among classes of ships within a given type (thus, weight was considered an independent variable in relationships defining manhour requirements), and (2) the hypothesized effects (U-shaped curves) appeared to exist within a ship class. Once the data were stratified by differences in ship weight, the U-shaped curves became even more evident.

Plots were made for each category of ships. Only the SSN data contained a range of construction periods broad enough to encompass a vivid delineation of the total hypothesis (i.e., reflecting a minimal manhour requirement). Plots for other types of ships, in general, indicated that manhour expenditures increased as the time to delivery increased, thus indicating that the optimal construction period had not been attained (Figure III-1). (It is possible, however, that some of the DLG (CG and FF) construction periods may have reached the optimal level.)

Note: Several points represent averages from multi-ship procurement contracts.

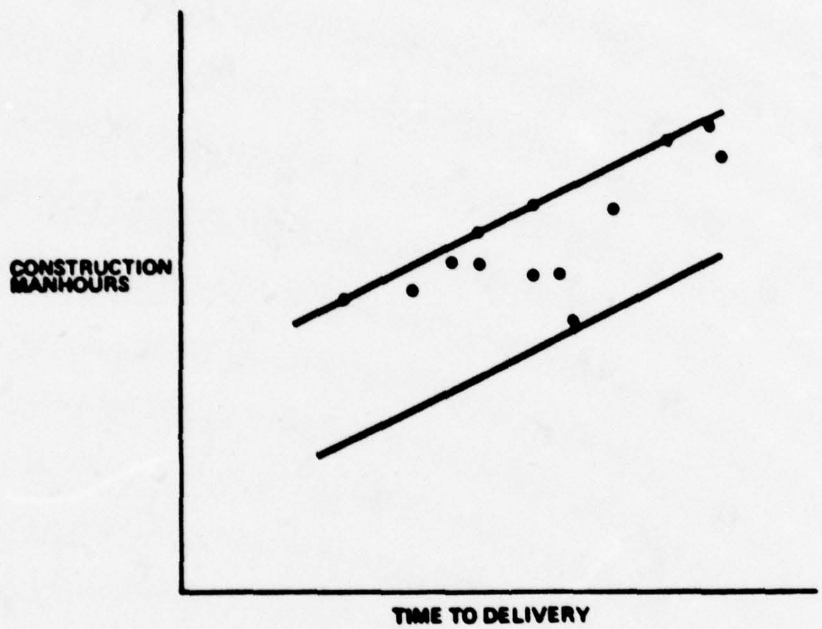

Figure III-1. Relationship Between Time-to-Delivery and Manhour Expenditures for DLGs

Effects of factors other than weight having a possible impact on construction manhours were more difficult to assess. The limited data precluded any analysis of differences between individual shipyards. Some scatter diagrams did indicate, however, that construction periods tended to be longer in Navy than in commerical shipyards and that for longer construction periods, manhour expenditures were less in commercial shipyards than in Navy shipyards for the same ship type.

The relationship between submarine construction manhour data and time to deliver is shown in Figure III-2. Here it is seen that Navy shipyards required more construction manhours for comparable construction periods. The SSBN data was adjusted for differences in weight to determine its location relative to the SSN data. As adjusted, it appears to be compatible with the SSN data and the hypothesis. Nevertheless, because of the narrow range in times to delivery for the SSBN submarines, no clear trend is evident. However, if the hypothesis is accepted and the trends in SSN data are applicable to SSBN submarines, one could conclude that the SSBN submarines were built in too short a construction time. That is, extending the construction period might have resulted in lower construction manhours. It appears that submarine construction planning may have been better than that for surface ships in the data sample; at least the optimal period was attained.

The relatively wide manhour dispersion (band) for the private shipyard data appeared to be caused--at least in part--by learning; this was confirmed by plotting manhours required for the Sturgeon Class, shown in Figure III-3. Learning was particularly evident in commercial yards when the length of the construction period was held roughly constant. For these yards, manhours incurred in the construction of the second and subsequent units were projected to unit one. A unit learning curve of 90 percent was assumed for purposes of this projection (approximately that reflected in Figure III-3). Figure III-4 shows the adjusted manhours as a function of the construction period; the band narrows considerably when the adjustment for learning is made.

Figure III-2

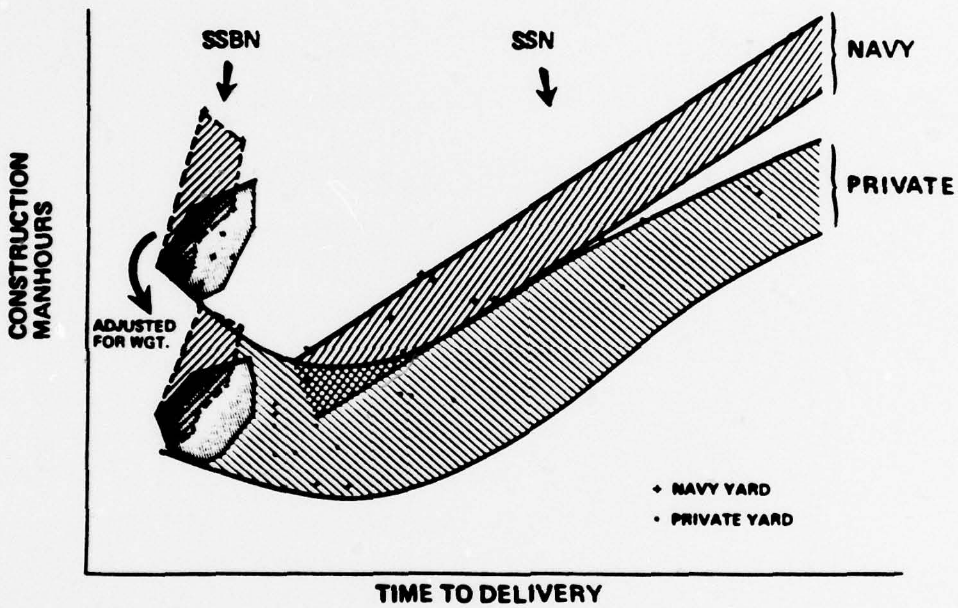

Figure III-2. Relationship Between Time-to-Delivery and Manhour Expenditures for SSN and SSBN Submarines

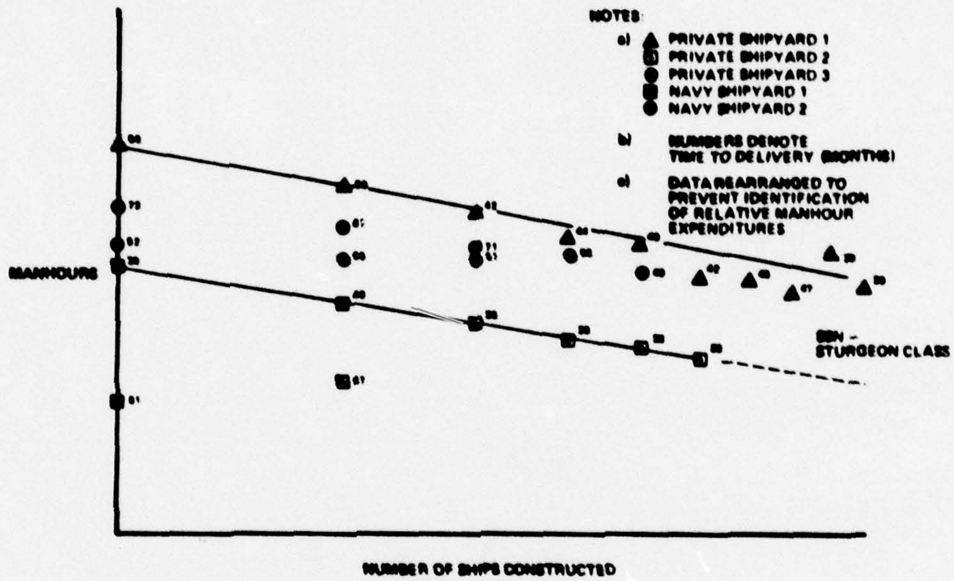

Figure III-3. Evidence of Learning (Most Evident in Private Yards Where Time-to-Delivery is Relatively Constant)

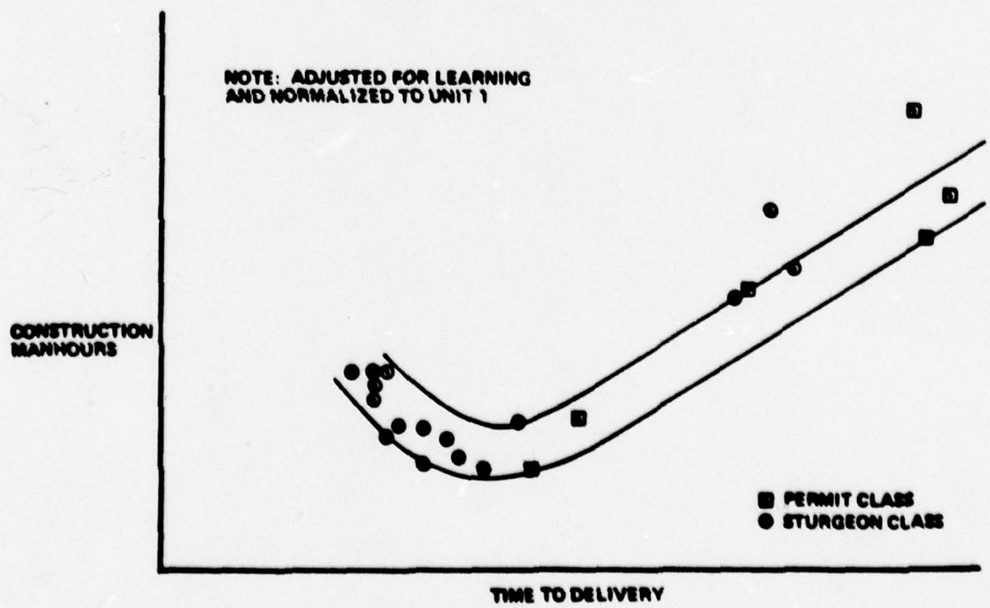

Figure III-4. Adjusted Relationship Between Time-to-Delivery and Manhour Expenditures for SSN Submarines Constructed in Commercial Yards

Manhour data was also plotted as a function of delivery time for surface auxiliaries. The amount of data was too limited to obtain definite curves for the different types and classes represented in the sample; however, the data did indicate that the hypothesized relationship probably exists for these ships. Figure III-5 indicates a combined effect of learning and time-to-delivery on manpower requirements for a class of amphibious ships. The greatest impact is probably due to learning.

In summary, the scatter diagrams for all types of ships for which data was available appear to support the hypothesis. Usually, only portions of the hypothesis were supported because the construction periods did not encompass the 'optimal' period. No available data refuted the hypothesis. The following reflects the elements of the hypothesis supported by the data sets reviewed (Curve segment L is the left-hand side and Curve segment R the right-hand side of the hypothesized curve):

- AE - supports curve segments L and R
- AFS - supports curve segments L and R
- AOR - supports curve segment R
- DE - supports curve segment R
- DLG - supports curve segment R
- LPD - supports curve segments L and R
- LPH - supports curve segment L
- LST - no clear indication, does not refute
- SSBN - no clear indication, does not refute
- SSN - supports curve segments L and R

Three scheduling parameters (time to launch, time to delivery, and time between 15 and 95 percent of the manhours expended) were used in the scatter diagrams. The time period reflecting the 80 percent increment of manhour expenditure, in general, encompassed the period over which the rate of manpower expenditure (i.e., average manloading) was maximum. In the statistical analysis of the data, however, time to delivery was used as the parameter. NAVSEA suggested that this period was more meaningful to planning

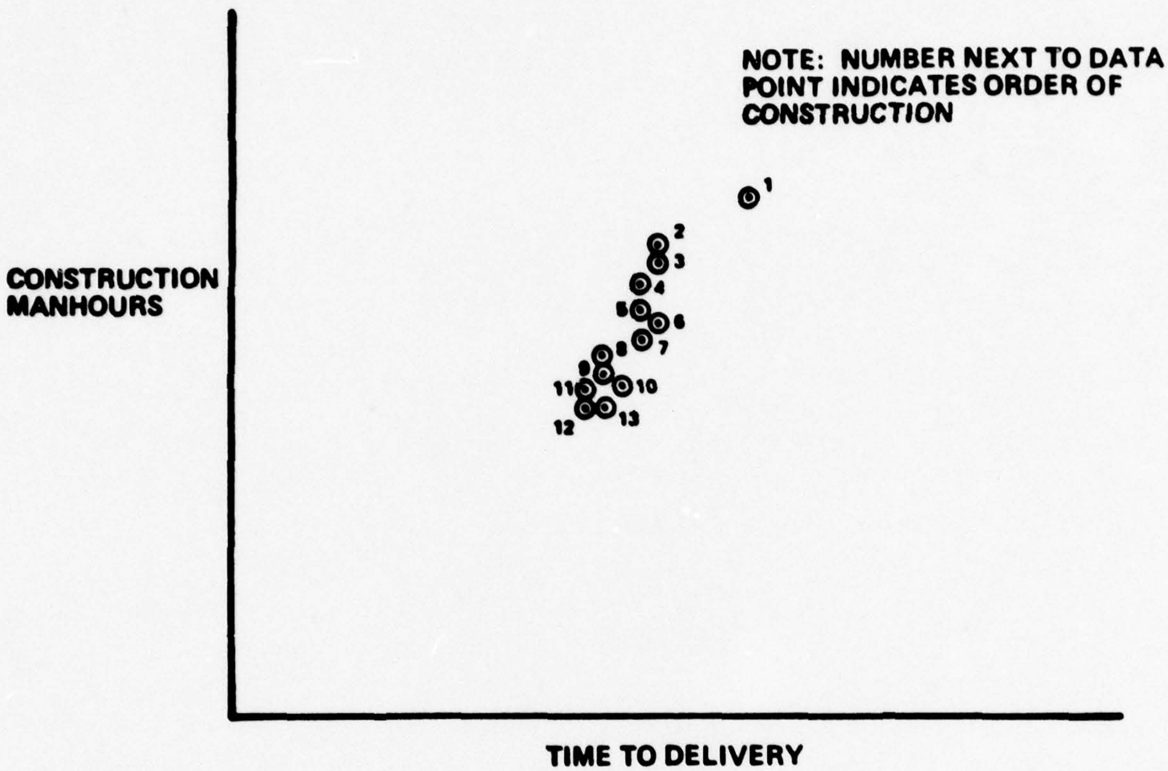

Figure III-5. Combined Effects of Learning and Time

and the most consistent in interpretation. Time to launch was considered to be dictated by shipyard policies and the business backlog (i.e., some ships are launched earlier than others of the same class to ensure that the way is available for construction of the next ship).

Analyses were performed on data sets within a ship category to evaluate the correlation among manhour expenditures, the scheduling parameters, the year in which ships were constructed, and the weight of the ship. The data showed that the manhours expended were not highly correlated with the year in which

ship construction was initiated (no strong evidence of decreased productivity over time in this pre-1970 data). The correlation analyses did not offer any new significant information; accepted and logical effects were found to occur (e.g., the weight of destroyers increased over time).

As noted previously, the small sample sizes within a ship type severely limited the statistical analysis that could be performed. Only two data sets, the SSN and the DLG (CG and FF), contained sufficient data to permit a statistical determination of values for model coefficients. Non-linear regression (Marquardt's Algorithm)[1] was used to derive the form of the relationship between construction manhours, the weight of the ship, and the construction period (time to delivery). Although the regression fits to the data were close (the R^2 values exceeded .99, and the residuals were low, usually less than 10 percent), the small sample sizes were detrimental to the statistical significance of the resultant equations. Because the samples were too small, no meaningful models could be developed for auxiliaries or for amphibious warships.

However, three equations[2] were derived from the regression: one for submarines and two for surface combatants (DLG). These equations are:

$$\text{Submarines: } M = 96{,}851.6\ W^{1.002}\ T^{-1.363} + 22.858\ W^{.434}T$$

$$\text{DLG (Navy Yards): } M = 3{,}800.6\ W^{.461}\ T^{-.462} + 13.240\ W^{.436}\ T$$

$$\text{DLG (Commercial Yards): } M = 4{,}075.4\ W^{.461}\ T^{-.462} + 11.007\ W^{.436}T$$

Where: M = construction manhours, in thousands
W = light ship weight, in thousands of tons (standard displacement for SSN)
T = time to delivery, in months

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1. Ibid.

2. It is stressed that these equations are preliminary and their usefulness is limited due to small sample sizes.

Using these relationships and nominal weight ranges encompassing the various classes of ships in the categories, upper and lower bounds were derived for manhour expenditures for the SSNs and DLGs. These bounds and Navy shipyard data are plotted in Figure III-6 for the SSNs and in Figure III-7 for the DLGs. Manhour data from commercial yards are not shown for proprietary reasons.

The curves do not appear to be a best fit to the data presented; this is because the relationships used in deriving the curves reflect the combined effects of both time to delivery and weight.

The SSN model reflects a more pronounced U-shape, the optimal point being around 50 months and well within the 33-month to 87-month range of times to deliver in the data base. Beyond this optimal point, the number of manhours required to complete construction increase rather sharply. The data did not reach a point of inflection, which is hypothesized to exist.

The DLG equation reflects an optimal point at around 30 months, the lower end of the 32-month to 60-month range of delivery time in the data. The right-hand term of the DLG model ($W^{.436}T$) is similar to that of the SSN equation ($W^{.434}T$), however, the left-hand terms differ significantly. The cause of this difference is not known; it may be due to differences in construction methods, ship design, and/or to the lack of DLG data for ships constructed in less than 30 months (problems of extrapolation beyond the range of the data).

The SSN equation, for short construction periods, reflects a steeper slope for a 4,000-ton submarine than a 2,500-ton submarine. This could indicate increased difficulty in completing larger ships in short periods of time, given the sequential operations that are performed over the construction period. On the other hand, this effect may be artificial; it may result from the stipulation that the exponent of weight in the left-hand term must be greater than the exponent of weight in the right-hand term, a necessary

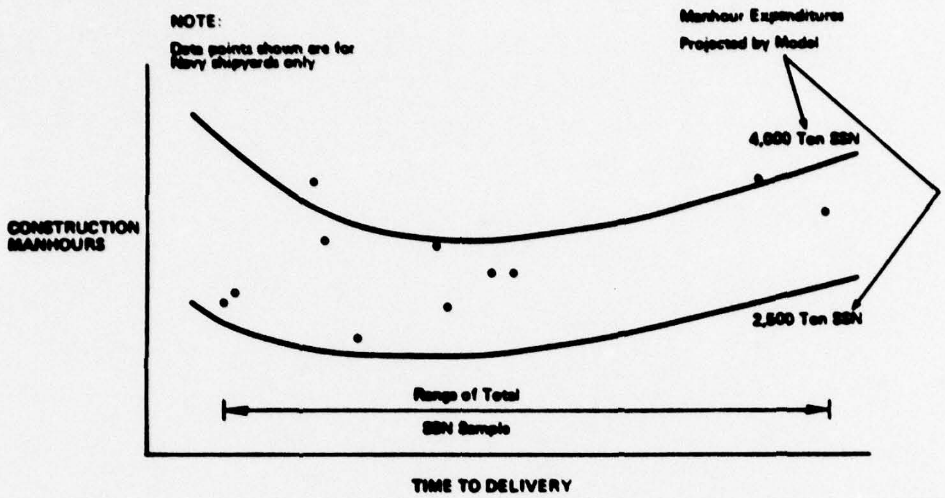

Figure III-6. Relationship Between Time-to-Delivery and Manhour Expenditures for SSN Submarines

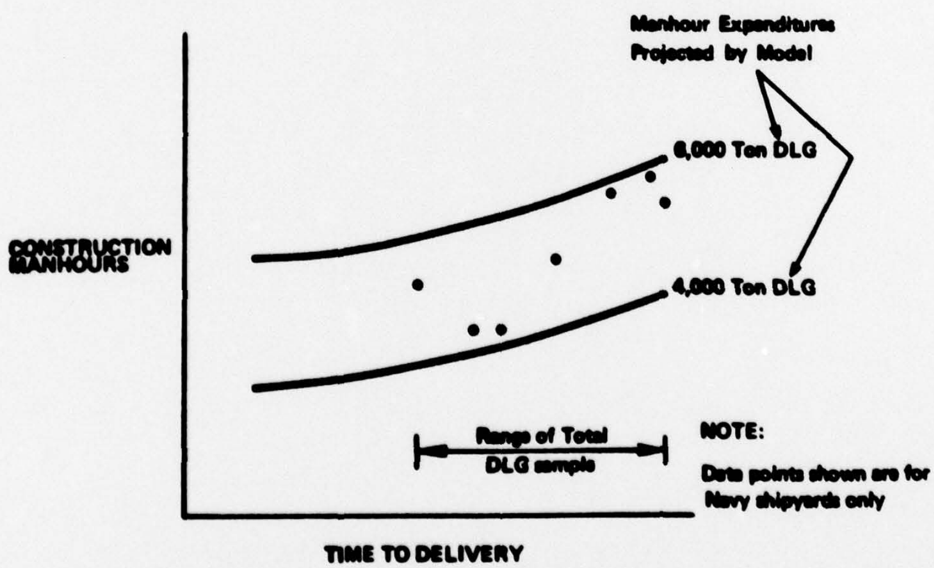

Figure III-7. Relationship Between Time-to-Delivery and Manhour Expenditure for DLGs

condition for the optimal construction time to increase as ship size increases. This aspect of the equation could be further investigated by adding a time-independent term (gW^h) to the equation. The addition of this term was not investigated at this time due to limited available manhour data. (Data has since been received which will permit the study of this effect.)

Comparisons of the DLG models for Navy and commercial shipyards reflect two potential, interesting phenomena. First, Navy shipyards appear to reflect lower manhour expenditures for shorter time spans and higher manhour expenditures for longer time spans than commercial yards; the crossover point is between 25 and 30 months (see Figure III-8). Secondly, the optimal time for Navy Shipyards is approximately 30 months as opposed to approximately 35 months for commercial yards. These apparent effects are subject to various interpretations. In general, however, it appears likely that the effects of a short time span (left-hand side of curve) do not differ between Navy and commercial shipyards; the differences projected with the data available are not significant. Also, the differences in optimal time (30 versus 35 months) are not that well defined; the impact on manhours over that time period is negligible (the curve is almost horizontal over the time frame of 27 to 40 months). The effects for longer time periods are probably real, and they are supported by the submarine data.

A somewhat cursory study was made of the impact of the rate at which manpower is allocated to shipbuilding on the resultant manpower expenditures. Figure III-9 shows the plots of manhour expenditures over time for a sample of SSN submarines of a specific class, and compares the resultant manhour expenditures with that projected by the SSN model. The rate of expenditures, reflected by the nominal slope of the curves, appears to have a significant impact on the overall expenditures (compare points D, E, and F with the other points). Limitations in the amount of data available early in the study precluded a statistical analysis of these effects or the subsequent development of an 'optimal' rate of expenditure associated with the minimum manpower expenditure at the optimal construction time. Certainly this is a dimension of the ship construction planning process requiring further study.

Most of the data obtained in this study reflected ship construction periods beyond the optimal. It is likely that this stratification of the data reflects the entire Navy construction program of prior years. Therefore, regardless of the amount of data available, it may be difficult to establish the equations for all types of ships identifying the optimal construction time. The development of generalized models for each ship category (vis-a-vis ship type, for which models have been derived in this study) may permit the derivation of the optimal times for all ships. Given the guidelines of the hypothesis, the analysis of a broader spectrum of data (across ship types) may effect a clear delineation of the transitional (optimal) time. The ability to isolate the optimal period subject to these data constraints warrants further study.

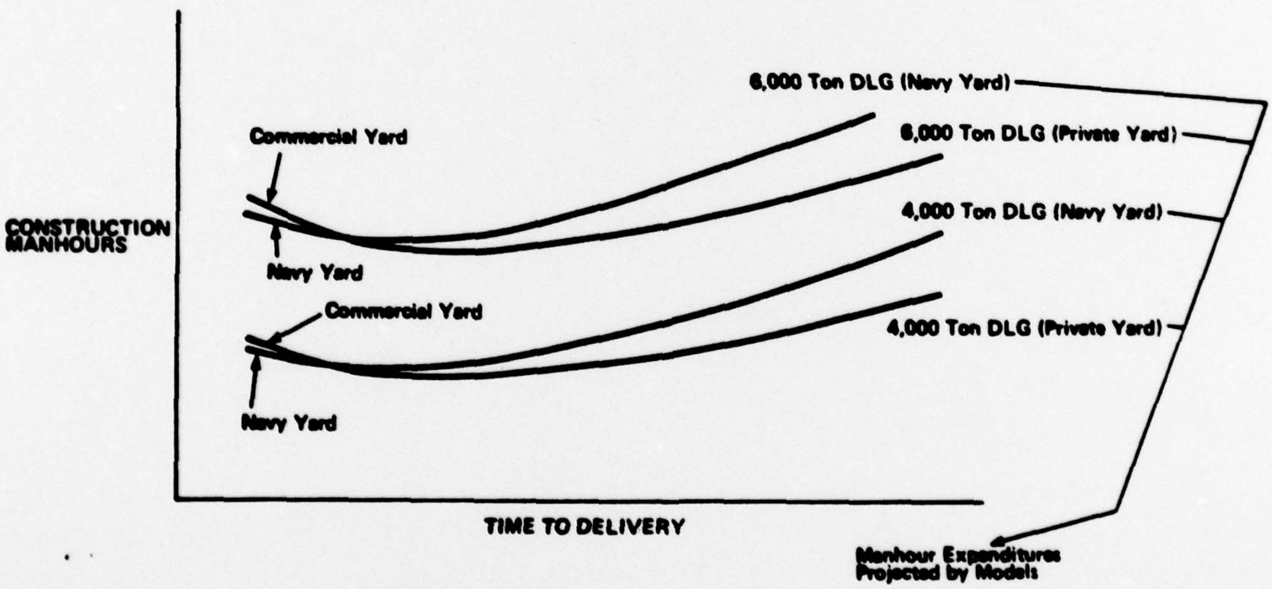

Figure III-8. Comparison of DLG Manhour Expenditures in Navy and Commercial Shipyards

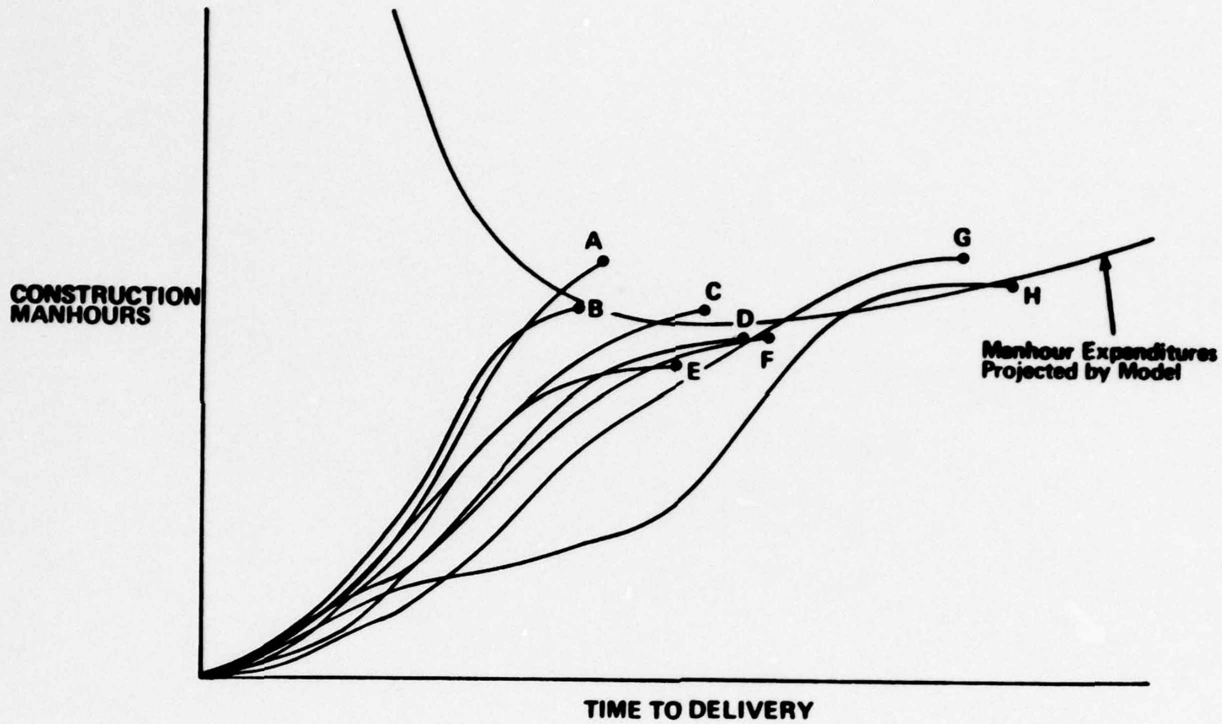

Figure III-9. Impact of Rate of Expenditures

IV. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The study findings confirm the basic hypothesis discussed in Section II. In general, the data provides greater support to the right-hand segment of the curve, where the number of manhours increases as the length of the construction period increases. This, perhaps, is the more critical of the two segments of the relationship. The left-hand portion of the curve derives from the logic which dictates that there is a minimum time for construction of a ship and it is likely that greater manhour expenditures will be required to complete ships in these minimum time spans.

In general, differences in optimal construction periods appeared to exist in the data samples among ship types and among ship classes within a type. The entire hypothesis (both left- and right-hand segments of the model curve) is supported by SSN construction data. The range of construction time periods in the historical data encompasses the optimal range. The range of the construction times in the data base for the DLGs (CGs and FFs) does not encompass both sides of the optimal construction time. The DLG data reflects increasing manhours as construction time increases (the influence of the Curve B segment), indicating that most of the construction periods for the DLGs in the sample exceeded the optimal construction period. However, because of the slope of the curve, it appears likely that some of the construction periods in the sample may have approached, if not encompassed, the optimum period.

The lack of a sufficient amount of manhour data precluded the development of models for all types of ships and a meaningful shipyard planning model which integrates the individual ship construction models into a shipyard operation. At no time did available data refute the hypothesis. Auxiliary ship data for some classes appeared to encompass the optimum construction period, but the small data set prevented statistical verification of this fact.

The validity of the statistical analysis used in developing the models was limited by an inadequate number of degrees of freedom resulting from the small sample sizes and the derivation of the several parameters required by the models. Although some models (presented in Section III) were derived, these analytical relationships must be regarded as preliminary; their statistical significance is limited by the degrees of freedom.

The small sample sizes also precluded possible model expansion from the basic models presented in Section II to reflect the following:

- a term which is independent of time,
- learning effects,
- shipyard differences,
- pre-launch versus post-launch time and manhour expenditure differences, and
- rate of manpower loading/total manhour implications.

Tests for the above effects require the derivation of additional parameter values and their associated error terms. Such tests would have been meaningless for equations with already limited statistical significance.

Other conclusions formulated from the study are as follows:

- Learning is evident in private shipyards (for submarines) when the construction period is relatively constant.
- The decreased productivity in commercial shipyards (over time) was not discernable in the limited data available to the study (pre-1970 data).
- In general, Navy shipyards required more manhours of labor than commercial shipyards to construct similar ships, especially for longer construction periods.
- Analytical models of a practical nature can be developed to assist shipyards in the planning process.
- Construction manhour data must be made more accessible to the research effort in order to develop effective and accurate planning models.

B. RECOMMENDATIONS

This study confirmed that improved models can be developed to enhance ship construction planning and decrease the resource requirements (manpower) of the construction. However, to effect improved shipyard operation, it is necessary that the models developed be applicable to a complete spectrum of Navy and commercial ship types. Therefore, consideration should be given to the development of planning models similar to those generated in this study for the remaining types of ships. Also, it is recommended that further research be undertaken to assess the viability of developing models applicable to broad categories of ships (e.g., submarines, surface combatants, auxiliaries, etc.). It would be intended that these generalized models also be applicable to plan the construction of new types of ships.

As noted previously, it appears that, to effect the optimum construction periods and the associated minimum construction manhours, the rate at which manpower is allocated to the construction process must be controlled and held within limits. The impact that the rate of allocation has upon the manpower requirements has not been determined. Consequently, to ensure the ship construction planning process has viable guides available, the effects of this important parameter on resultant resource requirements should be analyzed. These effects may be reflected as additional terms and variables in the algorithm of the planning models or as new dimensions to an overall planning process.

The individual and/or generalized models and the rate of manpower application models need then to be integrated into a shipyard planning model, probably a non-linear mathematical programming model, to effect optimization on a shipyard-wide basis. This would likely be similar to that proposed by Rhee.[1]

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1. Rhee, op. cit.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

In response to a need for improved guides to ship construction planning, a short-term research program was sponsored by the Office of Naval Research to determine if it is feasible to derive empirical models which reflect the impact of construction time and manloading on the resource requirements of ship construction. A hypothesis which defines the effects of the manloading and construction period on productivity was proposed and subsequently validated. CONT

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Inherent in the hypothesis is the existence of optimal construction periods and construction manloadings for ships.

A macro-analysis of ship construction data, the study resulted in the development of analytical models for individual ship types which define construction manpower requirements in terms of the weight of the ship and the length of the construction period. In addition, it was determined that optimum construction periods and associated minimum manhour requirements do exist for ships, and that this optimum scheduling is attained by an appropriate rate of manpower allocation.

Limitations in the amount of readily accessible data precluded the development of specific models applicable to all ship types. Since the research was considered preliminary, emphasis was given to isolating effects reflected in the available data rather than expanding the scope to include as many types of ships as possible. However, the analysis of the small data sets of ships for which models could not be developed further supported the existence of the effects reflected by the analytical relationships (no data sets refuted the hypothesis). Consequently, it is likely that the effects are relevant to all ship types, and that with adequate data, similar planning models can be developed for all ships.

Additional data was received throughout the six-month period of this preliminary research; there was not time to incorporate data received in the later phases of the study in the model construction. It was analyzed briefly to determine if it refuted the hypothesis; none did.

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